

Double beta decay experiments

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Abstract

The present status of double beta decay experiments are reviewed. The results of the most sensitive experiments, NEMO-3 and CUORICINO, are discussed. Proposals for future double beta decay experiments are considered. In these experiments sensitivity for the effective neutrino mass will be on the level of (0.1-0.01) eV.

1 Introduction

The current interest in neutrinoless double beta decay, $2\beta(0\nu)$ decay, is that the existence of this process is closely related to the following fundamental aspects of elementary- particle physics [1, 2, 3]: (i) lepton-number nonconservation, (ii) the presence of a neutrino mass and its origin, (iii) the existence of right-handed currents in electroweak interactions, (iv) the existence of the Majoron, (v) the structure of Higgs sector, (vi) supersymmetry, (vii) the existence of leptoquarks, (viii) the existence of a heavy sterile neutrino, and (ix) the existence of a composite neutrino.

All of these issues are beyond the standard model of electroweak interaction, therefore the detection of $2\beta(0\nu)$ decay would imply the discovery of new physics. Of course, interest in this process is caused primarily by the problem of a neutrino mass. If $2\beta(0\nu)$ decay is discovered, then according to current thinking, this will automatically mean that the rest mass of at least one neutrino flavor is nonzero and is of Majorana origin.

Interest in neutrinoless double beta decay has seen a significant rebirth in recent years after evidence for neutrino oscillations was obtained from the results of atmospheric [4] and solar [5, 6, 7, 8, 9] neutrino experiments (see, for example, the discussions in [10, 11, 12]).

This observation of oscillations was recently confirmed by the KamLAND experiment with reactor antineutrinos [13, 14] and by the new SNO result [15]. These results are an impressive proof that neutrinos have a nonzero mass. However, the experiments studying neutrino oscillations are not sensitive to the nature of the neutrino mass (Dirac or Majorana?) and provide no information

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on the absolute scale of the neutrino masses, since such experiments are sensitive only to the Δm^2 . The detection and study of $2\beta 0\nu$ decay may clarify the following problems of neutrino physics (see discussions in [16, 17, 18]): (i) neutrino nature; is the neutrino a Dirac or a Majorana particle?, (ii) absolute neutrino mass scale (a measurement or a limit on m_1), (iii) the type of neutrino mass hierarchy (normal, inverted, or quasidegenerate), (iv) CP violation in the lepton sector (measurement of the Majorana CP-violating phases).

Let us consider three main modes of 2β decay ¹:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu} \quad (1)$$

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- \quad (2)$$

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + \chi^0(+\chi^0) \quad (3)$$

$2\beta(2\nu)$ decay (process (1)) is a second-order process, which is not forbidden by any conservation law. The detection of this process furnishes information about nuclear matrix elements (NME) for 2ν transitions, and this makes it possible to test the existing models for calculating these NMEs and contributes to obtaining deeper insight into the nuclear-physics aspect of the problem of double beta decay. It is expected that the accumulation of experimental information about $2\beta(2\nu)$ processes will improve the quality of the calculations of NMEs, both for 2ν and for 0ν decay. Moreover, the study can yield a careful investigation of the time dependence of the coupling constant for weak interactions [19, 20].

$2\beta(0\nu)$ decay (process (2)) violates the law of lepton-number conservation ($\Delta L = 2$) and requires that the Majorana neutrino has a nonzero rest mass or that an admixture of right-handed currents be present in weak interaction. Also, this process is possible in some supersymmetric models, where $2\beta(0\nu)$ decay is initiated by the exchange of supersymmetric particles. This decay also arises in models featuring an extended Higgs sector within electroweak-interaction theory and in some other cases [1].

$2\beta(0\nu\chi^0)$ decay (process (3)) requires the existence of a Majoron - it is a massless Goldstone boson that arises upon a global breakdown of (B -L) symmetry, where B and L are, respectively, the baryon and the lepton number. The Majoron, if it exists, could play a significant role in the history of the early Universe and in the evolution of stars. The model of a triplet Majoron [21] was disproved in 1989 by the data on the decay width of the Z^0 boson that were obtained at the LEP accelerator (CERN, Switzerland). Despite this, some new models were proposed [22, 23], where $2\beta(0\nu\chi^0)$ decay is possible and where there are no contradictions with the LEP data. A 2β -decay model that involves

¹The decay modes also include $(A, Z) - (A, Z - 2)$ processes via (i) the emission of two positrons ($2\beta^+$ processes), (ii) the emission of one positron accompanied by electron capture ($EC\beta^+$ processes), and (iii) the capture of two orbital electrons (ECEC). For the sake of simplicity, we will consider $2\beta^-$ decay. In each case where it will be desirable to invoke $2\beta^+$, $EC\beta^+$, or ECEC processes, this will be indicated specifically.

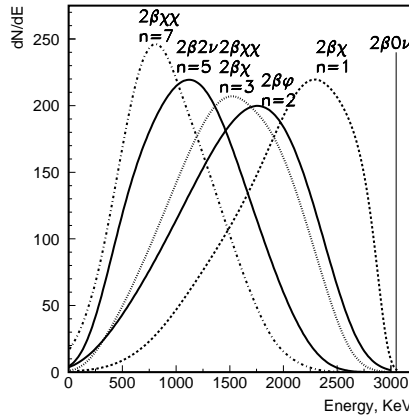


Figure 1: Energy spectra of different modes of $2\beta 2\nu$ ($n = 5$), $2\beta\chi^0$ ($n = 1, 2$ and 3) and $2\beta\chi^0\chi^0$ ($n = 3$ and 7) decays of ^{100}Mo .

the emission of two Majorons was proposed within supersymmetric theories [24] and several other models of the Majoron were proposed in the 1990s. By the term Majoron, one means here massless or light bosons that are associated with neutrinos. In these models, the Majoron can carry a lepton charge and is not required to be a Goldstone boson [25]. A decay process that involves the emission of two Majorons is also possible [26]. In models featuring a vector Majoron, the Majoron is the longitudinal component of a massive gauge boson emitted in 2β decay [27]. For the sake of simplicity, each such object is referred to here as a Majoron. In the Ref. [28], a bulk Majoron model was proposed in the context of the brane-bulk scenario for particle physics.

The possible two electrons energy spectra for different 2β decay modes of ^{100}Mo are shown in Fig. 1. Here n is spectral index, which defines the shape of the spectrum. For example, for ordinary Majoron $n = 1$, for 2ν decay $n = 5$, in case of bulk Majoron $n = 2$ and for the process with two Majoron emission $n = 3$ or 7 .

2 Results of experimental investigations

The number of possible candidates for double-beta decay is quite large - there are approximately 30 nuclei.² However, nuclei for which the double-beta-transition energy $E_{2\beta}$ is in excess of 2 MeV are of greatest interest, since the double-beta-

²Approximately the same number of nuclei can undergo double electron capture, while twenty nuclei and six nuclei can undergo, respectively, $\text{EC}\beta^+$ and $2\beta^+$ decay (see the tables in [29]).

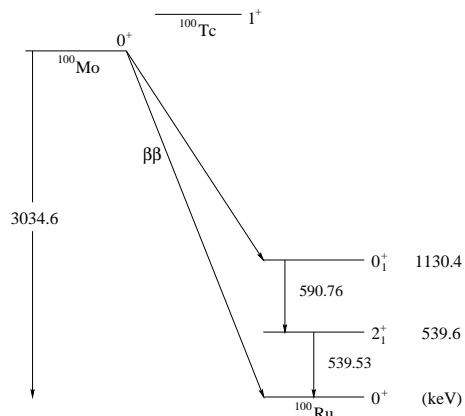


Figure 2: Levels scheme for ^{100}Mo - ^{100}Tc - ^{100}Ru .

decay probability strongly depends on the transition energy. In transitions to excited states of the daughter nucleus, the excitation energy is removed via the emission of one or two photons, which can be detected, and this can therefore serve as an additional source of information about double-beta decay. Fig. 2 shows the diagram of energy levels in the ^{100}Mo - ^{100}Tc - ^{100}Ru nuclear triplet (as example).

2.1 Two neutrino double beta decay

This decay was first recorded in 1949 in a geochemical experiment with ^{130}Te [30]; in 1967, it was also found for ^{82}Se [31]. Attempts to observe this decay in a direct experiment employing counters had been futile for a long time. Only in 1987 could M. Moe, who used a time-projection chamber (TPC), observe $2\beta(2\nu)$ decay in ^{82}Se for the first time [32]. Within the next few years, experiments employing counters were able to detect $2\beta(2\nu)$ decay in many nuclei. In ^{100}Mo [33, 34, 35], and ^{150}Nd [36] $2\beta(2\nu)$ decay to the 0^+ excited state of the daughter nucleus was recorded. Also, the $2\beta(2\nu)$ decay of ^{238}U was detected in a radiochemical experiment [37], and in a geochemical experiment for the first time the ECEC process was detected in ^{130}Ba [38]. Table 1 displays the present-day averaged and recommended values of $T_{1/2}(2\nu)$ from [39]. At the present-time, experiments devoted to detecting $2\beta(2\nu)$ decay are approaching a new level where it is insufficient to restrict oneself to recording the decay process, but it is necessary to measure numerous parameters of this process to a high precision. Tracking detectors that are able to record both the energy of each electron and the angle at which they diverge are the most appropriate instruments for solving this problem.

Table 1: Average and recommended $T_{1/2}(2\nu)$ values (from [39]).

Isotope	$T_{1/2}(2\nu)$
^{48}Ca	$4.3^{+2.1}_{-1.0} \cdot 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$
^{96}Zr	$(2.0 \pm 0.3) \cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$
$^{100}\text{Mo}-^{100}\text{Ru}(0_1^+)$	$(6.8 \pm 1.2) \cdot 10^{20}$
^{116}Cd	$(3.0 \pm 0.2) \cdot 10^{19}$
^{128}Te	$(2.5 \pm 0.3) \cdot 10^{24}$
^{130}Te	$(0.9 \pm 0.1) \cdot 10^{21}$
^{150}Nd	$(7.8 \pm 0.7) \cdot 10^{18}$
$^{150}\text{Nd}-^{150}\text{Sm}(0_1^+)$	$1.4^{+0.5}_{-0.4} \cdot 10^{20}$
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$
$^{130}\text{Ba}; \text{ECEC}(2\nu)$	$(2.2 \pm 0.5) \cdot 10^{21}$

2.2 Neutrinoless double beta decay

In contrast to two-neutrino decay, neutrinoless double-beta decay has not yet been observed ³, although from the experimental point of view, it is easier to detect it. In this case, one seeks, in the experimental spectrum, a peak of energy equal to the double-beta- transition energy and of width determined by the detectors resolution.

The present-day constraints on the existence of $2\beta(0\nu)$ decay are presented in Table 2 for the nuclei that are the most promising candidates. In calculating constraints on $\langle m_\nu \rangle$, the nuclear matrix elements from [43, 44, 45] were used (3-d column). It is advisable to employ the calculations from these studies, because the calculations are the most thorough and take into account the most recent theoretical achievements. The respective phase-space volumes were taken from [47]. In column four, limits on $\langle m_\nu \rangle$, which were obtained using the NMEs from a recent paper [46]. In this paper g_{pp} values (g_{pp} is parameter of QRPA theory) were fixed using experimental half-life values for 2ν decay and then $\text{NME}(0\nu)$ were calculated. Those authors analyze results of all existing QRPA calculations and demonstrate that their approach gives most accurate and reliable values for NMEs (but see, nevertheless, critics in [48]).

One can see from the Table 1 that in framework of NME calculations from [43, 44, 45] the limits on $\langle m_\nu \rangle$ for ^{130}Te and ^{100}Mo are comparable with ^{76}Ge

³The possible exception is the result with ^{76}Ge , published by a fraction of the Heidelberg-Moscow Collaboration, $T_{1/2} = 1.2 \cdot 10^{25}$ y [40] (see Table 2). The Moscow portion of the Collaboration does not agree with this conclusion [41] and there are others who are critical of this result [42]. Thus at the present time this "positive" result is not accepted by the " 2β decay community" and it has to be checked by new experiments.

results. And now one can not select any experiment as absolutely best one. From another side exactly the assemblage of sensitive experiments for different nuclei permits to increase reliability of the limit on $\langle m_\nu \rangle$. Present conservative limit can be set as 0.9 eV.

Table 2: Best present results on $2\beta(0\nu)$ decay (limits at 90% C.L.). ^{*}) Conservative limit from [53] is presented. ^{**}) Current experiments.

Isotope	$T_{1/2}$, y	$\langle m_\nu \rangle$, eV [43, 44, 45]	$\langle m_\nu \rangle$, eV [46]	Experiment
^{76}Ge	$> 1.9 \cdot 10^{25}$	$< 0.33 - 0.84$	$< 0.53 - 0.59$	HM [49]
	$\simeq 1.2 \cdot 10^{25}(?)$	$\simeq 0.5 - 1.3(?)$	$\simeq 0.7(?)$	Part of HM [40]
	$> 1.6 \cdot 10^{25}$	$< 0.36 - 0.92$	$< 0.58 - 0.64$	IGEX [50]
^{130}Te	$> 1.8 \cdot 10^{24}$	$< 0.4 - 0.9$	$< 1 - 1.6$	CUORICINO ^{**}) [51]
^{100}Mo	$> 4.6 \cdot 10^{23}$	$< 0.65 - 1.0$	$< 2.4 - 3.0$	NEMO-3 ^{**}) [52]
^{136}Xe	$> 4.5 \cdot 10^{23(*)}$	$< 0.8 - 4.7$	$< 2.9 - 5.6$	DAMA [53]
^{116}Cd	$> 1.7 \cdot 10^{23}$	$< 1.4 - 2.5$	$< 3.7 - 4.3$	SOLOTVINO [54]
^{82}Se	$> 1 \cdot 10^{23}$	$< 1.7 - 3.7$	$< 3.8 - 4.7$	NEMO-3 ^{**}) [52]

2.3 Double beta decay with Majoron emission

Table 3 displays the best present-day constraints for a ordinary ($n = 1$) Majoron. The nonstandard models of the Majoron were experimentally tested in [57] for ^{76}Ge and in [58] for ^{100}Mo , ^{116}Cd , ^{82}Se , and ^{96}Zr . Constraints on the decay modes involving the emission of two Majorons were also obtained for ^{100}Mo [59], ^{116}Cd [54], and ^{130}Te [60]. In recent NEMO Collaboration paper [55] new results of search for these processes in ^{100}Mo and ^{82}Se obtained with NEMO-3 detector were presented. Table 5 gives the best experimental constraints on decays accompanied by the emission of one or two Majorons (for $n = 2, 3$, and 7).

Hence at the present time only limits on double beta decay with Majoron emission have been obtained (see table 3 and 4). Conservative present limit on the coupling constant of ordinary Majoron to the neutrino is $\langle g_{ee} \rangle < 1.8 \cdot 10^{-4}$ [55].

3 Best present experiments

In this section the two large-scale current experiments NEMO-3 and CUORICINO are discussed.

Table 3: Best present results on $2\beta(0\nu\chi^0)$ decay (ordinary Majoron) at 90% C.L. The NME from the following works were used, 3-d column: [43, 44, 45], 4-th column: [46]. *) Conservative limit from [53] is presented.

Isotope	$T_{1/2}$, y	$\langle g_{ee} \rangle$, [43, 44, 45]	$\langle g_{ee} \rangle$, [46]
^{76}Ge	$> 6.4 \cdot 10^{22}$ [49]	$< (1.2 - 3.0) \cdot 10^{-4}$	$< (1.9 - 2.3) \cdot 10^{-4}$
^{82}Se	$> 1.5 \cdot 10^{22}$ [55]	$< (0.66 - 1.4) \cdot 10^{-4}$	$< (1.2 - 1.9) \cdot 10^{-4}$
^{100}Mo	$> 2.7 \cdot 10^{22}$ [55]	$< (0.4 - 0.7) \cdot 10^{-4}$	$< (1.6 - 1.8) \cdot 10^{-4}$
^{116}Cd	$> 8 \cdot 10^{21}$ [54]	$< (1.0 - 2.0) \cdot 10^{-4}$	$< (2.8 - 3.3) \cdot 10^{-4}$
^{128}Te	$> 2 \cdot 10^{24}(\text{geochem})$ [56]	$< (0.7 - 1.6) \cdot 10^{-4}$	$< (1.9 - 2.4) \cdot 10^{-4}$
^{136}Xe	$> 1.6 \cdot 10^{22(*)}$ [53]	$< (0.7 - 5.0) \cdot 10^{-4}$	$< (3.4 - 4.4) \cdot 10^{-4}$

Table 4: Best present limits on $T_{1/2}$ for decay with one and two Majorons at 90% C.L. for modes with spectral index $n = 2$, $n = 3$ and $n = 7$.

Isotope	$n = 2$	$n = 3$	$n = 7$
^{76}Ge	-	$> 5.8 \cdot 10^{21}$ [57]	$> 6.6 \cdot 10^{21}$ [57]
^{82}Se	$> 6 \cdot 10^{21}$ [55]	$> 3.1 \cdot 10^{21}$ [55]	$> 5 \cdot 10^{20}$ [55]
^{96}Zr	-	$> 6.3 \cdot 10^{19}$ [58]	$> 2.4 \cdot 10^{19}$ [58]
^{100}Mo	$> 1.7 \cdot 10^{22}$ [55]	$> 1 \cdot 10^{22}$ [55]	$> 7 \cdot 10^{19}$ [55]
^{116}Cd	$> 1.7 \cdot 10^{21}$ [54]	$> 8 \cdot 10^{20}$ [54]	$> 3.1 \cdot 10^{19}$ [54]
^{130}Te	-	$> 9 \cdot 10^{20}$ [60]	-

3.1 NEMO-3 experiment [52, 62, 61]

This is a tracking experiment that, in contrast to experiments with ^{76}Ge , detects not only the total energy deposition, but also other parameters of the process, including the energy of the individual electrons, angle between them, and the coordinates of the event in the source plane. The performance of the detector was studied with the NEMO-2 prototype [63]. Since June of 2002, the NEMO-3 detector has operated at the Frejus Underground Laboratory (France) located at a depth of 4800 m w.e. The detector has a cylindrical structure and consists of 20 identical sectors (see Fig 3). A thin (about 30-60 mg/cm²) source containing beta-decaying nuclei and having a total area of 20 m² and a weight of up to 10 kg was placed in the detector. The basic principles of detection are identical to those used in the NEMO-2 detector. The energy of the electrons is measured by plastic scintillators (1940 individual counters), while the tracks are reconstructed on the basis of information obtained in the planes of Geiger cells (6180 cells)

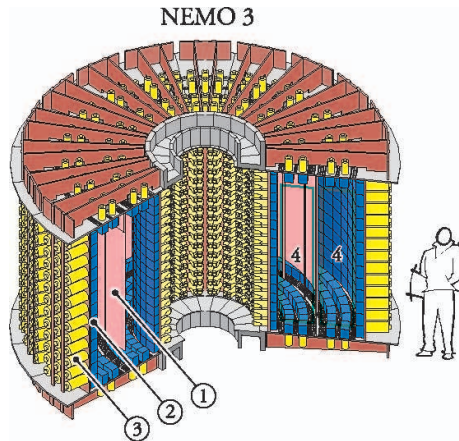


Figure 3: The NEMO-3 detector without shielding. 1 – source foil; 2– plastic scintillator; 3 – low radioactivity PMT; 4 – tracking chamber.

surrounding the source on both sides. The tracking volume of the detector is filled with a mixture consisting of $\sim 95\%$ He, 4% alcohol, 1% Ar and 0.1% water at slightly above atmospheric pressure. In addition, a magnetic field of strength of about 25 G parallel to the detector axis is created by a solenoid surrounding the detector. The magnetic field is used to identify electron-positron pairs and, hence, to suppress this source of background.

The main characteristics of the detector are the following: the energy resolution of the scintillation counters lies in the interval 14-17% FWHM for electrons of energy 1 MeV; the time resolution is 250 ps for an electron energy of 1 MeV; and the accuracy in reconstructing of the vertex of $2e^-$ events is about 1 cm. The detector is surrounded by a passive shield consisting of 20 cm of steel and 30 cm of water. The level of radioactive impurities in structural materials of the detector and of the passive shield was tested in measurements with low-background HPGe detectors.

Measurements with the NEMO-3 detector revealed that tracking information, combined with time and energy measurements, makes it possible to suppress the background efficiently. That NEMO-3 can be used to investigate almost all isotopes of interest is a distinctive feature of this facility. At the present time, such investigations are being performed for seven isotopes; these are ^{100}Mo , ^{82}Se , ^{116}Cd , ^{150}Nd , ^{96}Zr , ^{130}Te , and ^{48}Ca (see Table 5). In addition, foils from copper and natural (not enriched) tellurium are placed in the detector for performing background measurements.

Fig. 4 and Fig. 5 display the spectrum of $2\beta(2\nu)$ events, in ^{100}Mo and ^{82}Se that were collected over 389 days [52]. For ^{100}Mo angular distribution (Fig. 4b) and single electron spectrum (Fig. 4c) are also shown. The total number of useful events is about 219,000 which is much greater than the total statistics

Table 5: Investigated isotopes with NEMO-3

Isotope	^{100}Mo	^{82}Se	^{130}Te	^{116}Cd	^{150}Nd	^{96}Zr	^{48}Ca
Enrichment, %	97	97	89	93	91	57	73
Mass of isotope, g	6914	932	454	405	36.6	9.4	7.0

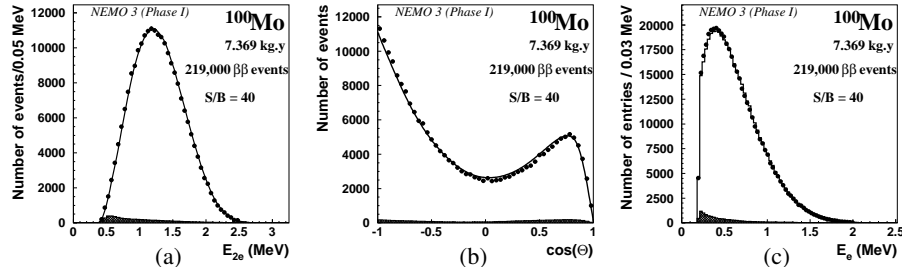


Figure 4: (a) Energy sum spectrum of the two electrons, (b) angular distribution of the two electrons and (c) single energy spectrum of the electrons, after background subtraction from ^{100}Mo with 7.369 kg-years exposure [52]. The solid line corresponds to the expected spectrum from $2\beta(2\nu)$ simulations and the shaded histogram is the subtracted background computed by Monte-Carlo simulations.

of all of the preceding experiments with ^{100}Mo (and even greater then total statistics of all previous 2β decay experiments!). It should also be noted that the background is as low as about 2.5% of the total number of useful events. By employing the calculated values of the detection efficiencies for $2\beta(2\nu)$ events, the following half-life values were obtained for ^{100}Mo and ^{82}Se :

$$T_{1/2}(^{100}\text{Mo}; 2\nu) = [7.11 \pm 0.02(\text{stat}) \pm 0.54(\text{syst})] \cdot 10^{18} \text{ y} \quad (4)$$

$$T_{1/2}(^{82}\text{Se}; 2\nu) = [9.6 \pm 0.3(\text{stat}) \pm 1.0(\text{syst})] \cdot 10^{19} \text{ y} \quad (5)$$

These results and results for ^{116}Cd , ^{96}Zr and ^{150}Nd are presented in Table 6. Notice that values for ^{100}Mo and ^{116}Cd have been obtained on the assumption that SSD mechanism is valid ⁴ [64, 65]. Systematic uncertainties can be decreased using special calibrations and can be improved up to $\sim (3 - 5)\%$.

⁴Validity of SSD mechanism in ^{100}Mo was demonstrated using analysis of single electron spectrum (see [62]). In the case of ^{116}Cd this is still a hypothesis.

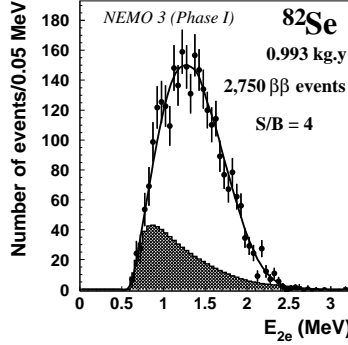


Figure 5: Energy sum spectrum of the two electrons after background subtraction from ^{82}Se with 0.993 kg-years exposure (same legend as Fig. 4) [52]. The signal contains 2,750 2β events and the signal-to-background ratio is 4.

Table 6: Two neutrino half-life values for different nuclei obtained in the NEMO-3 experiment (for ^{116}Cd , ^{96}Zr and ^{150}Nd results are preliminary). First error is statistical and second is systematic. S/B is the signal-to-background ratio.

Isotope	Measurement time, days	Number of 2ν events	S/B	$T_{1/2}(2\nu)$, y
^{100}Mo	389	219000	40	$(7.11 \pm 0.02 \pm 0.54) \cdot 10^{18}$
^{82}Se	389	2750	4	$(9.6 \pm 0.3 \pm 1.0) \cdot 10^{19}$
^{116}Cd	168.4	1371	7.5	$(2.8 \pm 0.1 \pm 0.3) \cdot 10^{19}$
^{96}Zr	168.4	72	0.9	$(2.0 \pm 0.3 \pm 0.2) \cdot 10^{19}$
^{150}Nd	168.4	449	2.8	$(9.7 \pm 0.7 \pm 1.0) \cdot 10^{18}$

Fig. 6 show the tail of the two-electron energy sum spectrum in the $2\beta(0\nu)$ energy window for ^{100}Mo and ^{82}Se . One can see that experimental spectrum is in good agreement with calculated spectrum, which was obtained taking into account all sources of background. Using a maximal likelihood method the following limits on neutrinoless double beta decay of ^{100}Mo and ^{82}Se (mass mechanism; 90% C.L.) have been obtained:

$$T_{1/2}(^{100}\text{Mo}; 0\nu) > 4.6 \cdot 10^{23} \text{ y} \quad (6)$$

$$T_{1/2}(^{82}\text{Se}; 0\nu) > 1 \cdot 10^{23} \text{ y} \quad (7)$$

These limits are approximately one order of magnitude better than results of previous experiments [66, 67].

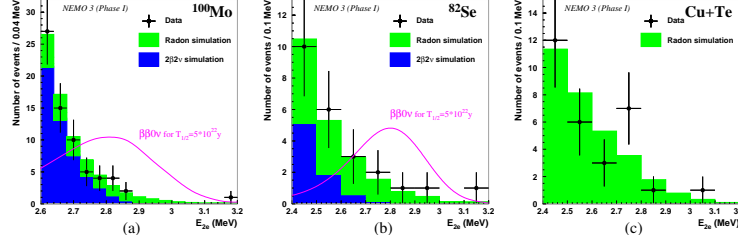


Figure 6: Spectra of the energy sum of the two electrons in the $2\beta(0\nu)$ energy window after 389 effective days of data collection from February 2003 until September 2004 (Phase I): (a) with 6.914 kg of ^{100}Mo ; (b) with 0.932 kg of ^{82}Se ; (c) with Copper and Tellurium foils [52]. The shaded histograms are the expected backgrounds computed by Monte-Carlo simulations: dark (blue) is the $2\beta(2\nu)$ contribution and light (green) is the Radon contribution. The solid line corresponds to the expected $2\beta(0\nu)$ signal if $T_{1/2} = 5 \times 10^{22}$ y.

Using NME values from [43, 44, 45] the bound on $\langle m_\nu \rangle$ is 0.65–1.0 eV for ^{100}Mo and 1.7–3.7 eV for ^{82}Se . If one will use NMEs from [46] then $\langle m_\nu \rangle < 2.4 - 3.0$ eV and $< 3.8 - 4.7$ eV, respectively.

In this experiment the best present limits on all possible modes of double beta decay with Majoron emission have been obtained [55] too (see Tables 3 and 4).

For this first running period (Phase I) presented here, radon was the dominant background in $2\beta(0\nu)$ decay energy region. It has now been significantly reduced by a factor ~ 10 by a radon-tight tent enclosing the detector and a radon-trap facility in operation since December 2004 which has started a second running period (Phase II). After five years of data collection, the expected sensitivity at 90% C.L will be $T_{1/2}(\beta\beta 0\nu) > 2 \times 10^{24}$ y for ^{100}Mo and 8×10^{23} y for ^{82}Se , corresponding to $\langle m_\nu \rangle < 0.3 - 1.4$ eV for ^{100}Mo and $\langle m_\nu \rangle < 0.6 - 1.7$ eV for ^{82}Se . At the same time the search for decay with Majoron emission with record sensitivity and precise investigation of $2\beta(2\nu)$ decay in seven mentioned above nuclei will be continued.

3.2 CUORICINO [51]

This program is the first stage of the larger CUORE experiment (see Subsection 4.1). The experiment is running at the Gran Sasso Underground Laboratory in Italy (3500 m w.e.). The detector consists of low-temperature devices based on $^{nat}\text{TeO}_2$ crystals. The use of natural tellurium is justified in this case, because the content of ^{130}Te in it is rather high, 33.8%. The detector consists of 62 individual crystals, their total weight being 40.7 kg. The energy resolution is 7.5–9.6 keV at an energy of 2.6 MeV.

The experiment has been running since March of 2003. The summed spectra

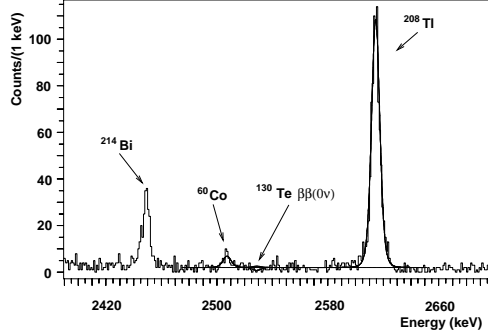


Figure 7: The sum spectra of all crystal in the region of the $2\beta(0\nu)$ energy [51].

of all crystals in the region of the $2\beta(0\nu)$ energy is shown in Fig. 7. The total exposure is $3.09 \text{ kg} \cdot \text{y}$ (^{130}Te). The background at the energy of the $2\beta(0\nu)$ decay is $0.18 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$. No peak is evident and the limit is $T_{1/2} > 1.8 \cdot 10^{24} \text{ y}$ (90% C.L.)⁵.

Using NME values from [43, 44, 45] the limit on $\langle m_\nu \rangle$ is less than 0.4-0.9 eV. If one uses the NME from [46] then $\langle m_\nu \rangle < 1.1 - 1.6 \text{ eV}$.

The sensitivity of the experiment to $2\beta(0\nu)$ decay of ^{130}Te under present conditions will be on the level of $\sim 4 \cdot 10^{24}$ at 90% C.L. for 5 y of measurement. This in turn means the sensitivity to $\langle m_\nu \rangle$ is on the level of 0.3-0.9 eV. At the same time there is a hope to detect $2\beta(2\nu)$ decay of ^{130}Te in this experiment.

One of the tasks of the CUORICINO experiment is to demonstrate the possibility of substantially reducing of the background to the level of $0.01\text{-}0.001 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$ which is necessary to proceed with the CUORE Project (see section 4.1).

4 Planned experiments

In this section, mention of five most developed and promising experiments which can be realized within the next five to ten years is discussed (see Table 7). The estimation of the sensitivity in all experiments is made using NMEs from [43, 44, 45, 46].

4.1 CUORE [68]

This experiment is to be run at the Gran Sasso Underground Laboratory (Italy; 3500 m w.e.). The plan is to investigate 760 kg of $^{nat}\text{TeO}_2$, with a total of 206

⁵It should be stressed that "sensitivity" of the experiment under present conditions (when number of observed events is equal to expected mean background) is $\sim 1 \cdot 10^{24} \text{ y}$ (90% C.L.). Much better limit was obtained due to big "negative" fluctuation of the background in the 0ν energy region.

Table 7: Five most developed and promising projects (see text). Sensitivity at 90% C.L. for three (1-st step of GERDA and MAJORANA) five (EXO, SuperNEMO) and ten (CUORE, full-scale GERDA and MAJORANA) years of measurements is presented. [^{*}) For the background $0.001 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$; ^{**}) for the background $0.01 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$.]

Experiment	Isotope	Mass of isotope, kg	Sensitivity $T_{1/2}$, y	Sensitivity $\langle m_\nu \rangle$, meV	Status
CUORE [68]	^{130}Te	200	$4.6 \cdot 10^{26*})$ $1.4 \cdot 10^{26**})$	30-100 40-170	accepted
GERDA [69]	^{76}Ge	40 500	$2 \cdot 10^{26}$ $4 \cdot 10^{27}$	90-300 20-70	accepted R&D
MAJORANA [72, 73]	^{76}Ge	180 500	$5 \cdot 10^{26}$ $4 \cdot 10^{27}$	60-200 20-70	R&D R&D
EXO [74]	^{130}Xe	200 1000	$6.4 \cdot 10^{25}$ $8 \cdot 10^{26}$	70-400 12-86	accepted R&D
SuperNEMO [76, 77, 78]	^{82}Se	100	$(1 - 2) \cdot 10^{26}$	40-150	R&D

kg of ^{130}Te . One thousand low-temperature ($\sim 8 \text{ mK}$) detectors, each having a weight of 760 g, will be manufactured and arranged in 25 towers (one tower is approximately equivalent to the CUORICINO detector, see Subsection 3.2). Planned energy resolution is 5 keV (FWHM). One of the main problems here is to reduce the background level by a factor of about 10 to 100 in relation to the background level achieved in the detector CUORICINO [51]. Upon reaching a background level of $0.001 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$, the sensitivity of the experiment to the 0ν decay of ^{130}Te for 10 y of measurements and at 90% C.L. will become approximately $4.6 \cdot 10^{26} \text{ y}$ ($\langle m_\nu \rangle \sim 0.03\text{-}0.1 \text{ eV}$). For more realistic level of background $0.01 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$ sensitivity will be $\sim 1.4 \cdot 10^{26} \text{ y}$ for half-life and $\sim 0.04\text{-}0.17 \text{ eV}$ for effective Majorana neutrino mass.

The experiment has been approved and funded.

4.2 GERDA [69]

This is one of two (along with the MAJORANA experiment) planned experiments with ^{76}Ge . The experiment is to be located in Gran Sasso Underground Laboratory (3500 m w.e.). The proposal is based on ideas and approaches which were proposed for GENIUS [1] and the GEM [70] experiments. The plan is to place "naked" HPGe detectors in highly purified liquid nitrogen. It minimizes the weight of construction material near the detectors and, as a result, decreases the level of background. The liquid nitrogen dewar is placed into a vessel of very

pure water. The water plays a role of passive and active (Cherenkov radiation) shield.

The proposal involves three phases. In the first phase, the existing HPGe detectors (~ 15 kg), which previously were used in Heidelberg-Moscow [49] and IGEX [50] experiments, will be utilized. In the second phase ~ 40 kg of enriched Ge will be investigated. In the third phase the plan is to use ~ 500 kg of ^{76}Ge .

The first phase, lasting one year, is to measure the sensitivity to $3 \cdot 10^{25}$ y, which gives a possibility to checking the "positive" result of [40]. The sensitivity of the second phase (for three years of measurement) will be $\sim 2 \cdot 10^{26}$ y, which corresponds to a sensitivity for $\langle m_\nu \rangle$ on the level of $\sim 0.09\text{--}0.3$ eV.

The first two phases have been approved and funded. Measurements will start in $\sim 2007(2008)$. The results of this first step will play an important role in the decision to support the full scale experiment.

The project is very promising although it will be difficult to reach the desired level of background. One of the significant problems is ^{222}Rn in the liquid nitrogen (see, for example, results of [71]).

4.3 MAJORANA [72, 73]

The MAJORANA facility will consist of 210 sectioned HPGe detectors manufactured from enriched germanium (the degree of enrichment is about 86%). The total mass of enriched germanium will be 500 kg. The facility is designed in such a way that it will consist of ten individual supercryostats manufactured from low radioactive copper, each containing 21 HPGe detectors. The entire facility will be surrounded by a passive shield and will be located at an underground laboratory in Canada (or in the United States). Only the total energy deposition will be utilized in measuring the $2\beta(0\nu)$ decay of ^{76}Ge to the ground state of the daughter nucleus. The use of sectioned HPGe detectors, pulse shape analysis, anticoincidence, and low radioactivity structural materials will make it possible to reduce the background to a value below $3 \cdot 10^{-4} \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$ and to reach a sensitivity of about $4 \cdot 10^{27}$ y within ten years of measurements. The corresponding sensitivity to the effective mass of the Majorana neutrino is about 0.02 to 0.07 eV. The measurement of the $2\beta(0\nu)$ decay of ^{76}Ge to the 0^+ excited state of the daughter nucleus will be performed by recording two cascade photons and two beta electrons. The planned sensitivity for this process is about 10^{27} y.

In the first step ~ 180 kg of ^{76}Ge will be investigated. It is anticipated that in the sensitivity to $2\beta(0\nu)$ decay to the ground state of the daughter nuclei for 3 years of measurement will be $5 \cdot 10^{26}$ y. It will reject or to confirm the "positive" result from [40]. Sensitivity to $\langle m_\nu \rangle$ will be $\sim 0.06\text{--}0.2$ eV. During this time different methods and technical questions will be checked and possible background problems will be investigated.

4.4 EXO [74]

In this experiment the plan is to implement M. Moe's proposal of 1991 [75]. Specifically it is to record both ionization electrons and the Ba^+ ion originating from the double-beta-decay process $^{136}\text{Xe} - ^{136}\text{Ba}^{++} + 2e^-$. In reference [74], it is proposed to operate with 1t of ^{136}Xe . The actual technical implementation of the experiment has not yet been developed. One of the possible schemes is to fill a TPC with liquid enriched xenon. To avoid the background from the 2ν decay of ^{136}Xe , the energy resolution of the detector must not be poorer than 3.8% (FWHM) at an energy of 2.5 MeV (ionization and scintillation signals will be detected).

In the 0ν decay of ^{136}Xe , the TPC will measure the energy of two electrons and the coordinates of the event to within a few millimeters. After that, using special stick Ba ion will be removed from the liquid and then will be registered in special cell by resonance excitation. For Ba^{++} to undergo a transition to a state of Ba^+ , a special gas is added to xenon. The authors of the project assume that the background will be reduced to one event within five years of measurements. Given 70% detection efficiency it will be possible to reach a sensitivity of about $8 \cdot 10^{26}$ y for the ^{136}Xe half-life and a sensitivity of about 0.012 to 0.086 eV for the neutrino mass.

The authors also considered a detector in which the mass of ^{136}Xe is 10 t, but this is probably beyond present-day capabilities. It should be noted that about 100 t of natural xenon are required to obtain 10 t of ^{136}Xe . This exceeds the xenon produced worldwide over several years.

One should note that the principle difficulty in this experiment is associated with detecting the Ba^+ ion with a reasonably high efficiency under conditions of real experiment. This issue calls for thorough experimental tests, and positive results along these lines have yet to be obtained.

As the first stage of the experiment it is planned the EXO-200 will use 200 kg of ^{136}Xe without Ba ion registration. This experiment is currently under preparation and measurement will start probably in 2007(2008). The 200 kg of enriched Xe is a product of Russia (enrichment is $\sim 80\%$). If the background will be 40 events within 5 y of measurements, as estimated by the authors, then the sensitivity of the experiment will be $\sim 6 \cdot 10^{25}$ y (this corresponds to sensitivity for $\langle m_\nu \rangle$ at the level ~ 0.07 -0.4 eV). This initial prototype will operate at the Waste Isolation Pilot Plant (WIPP) in Southern New Mexico (USA).

4.5 SuperNEMO [76, 77, 78]

The NEMO Collaboration has studied and is pursuing an experiment that will observe 100 kg of ^{82}Se with the aim of reaching a sensitivity to the 0ν decay mode at the level of $T_{1/2} \sim (1 - 2) \cdot 10^{26}$ y (the corresponding sensitivity to the neutrino mass is about 0.04 to 0.15 eV). In order to accomplish this goal, it is proposed to use the experimental procedures nearly identical to that in the NEMO-3 experiment (see Subsection 3.1). The new detector will have planar geometry and will consist of 20 identical modules (5 kg of ^{82}Se in each sector).

A ^{82}Se source having a thickness of about 40 mg/cm^2 and a very low content of radioactive admixtures is placed at the center of the modules. The detector will again record all features of double beta decay: the electron energy will be recorded by counters based on plastic scintillators ($\Delta E/E \sim 10-12\%(FWHM)$) at $E = 1\text{ MeV}$, while tracks will be reconstructed with the aid of Geiger counters. The same device can be used to investigate ^{100}Mo , ^{116}Cd , and ^{130}Te with a sensitivity to $2\beta(0\nu)$ decay at a level of about $(0.5 - 1) \cdot 10^{26}\text{ y}$.

The use of an already tested experimental technique is an appealing feature of this experiment. The plan is to arrange the equipment at the new Frejus Underground Laboratory (France; the respective depth being 4800 m w.e.) or at CANFRANC Underground Laboratory (Spain; 2500 m w.e.). The experiment is currently in its R&D stage.

5 Conclusion

In conclusion, two-neutrino double-beta decay has so far been recorded for ten nuclei (^{48}Ca , ^{76}Ge , ^{82}Se , ^{96}Zr , ^{100}Mo , ^{116}Cd , ^{128}Te , ^{130}Te , ^{150}Nd , ^{238}U). In addition, the $2\beta(2\nu)$ decay of ^{100}Mo and ^{150}Nd to 0^+ excited state of the daughter nucleus has been observed and the ECEC(2ν) process in ^{130}Ba was recorded. Experiments studying two-neutrino double beta decay are presently approaching a qualitatively new level, where high-precision measurements are performed not only for half-lives but also for all other parameters of the process. As a result, a trend is emerging toward thoroughly investigating all aspects of two-neutrino double-beta decay, and this will furnish very important information about the values of nuclear matrix elements, the parameters of various theoretical models, and so on. In this connection, one may expect advances in the calculation of nuclear matrix elements and in the understanding of the nuclear-physics aspects of double beta decay.

Neutrinoless double beta decay has not yet been confirmed. There is a conservative limit on the effective value of the Majorana neutrino mass at the level of 0.9 eV . Within the next few years, the sensitivity to the neutrino mass in the CUORICINO and NEMO-3 experiments will be improved to become about 0.3 to 0.9 eV with measurements of ^{130}Te and ^{100}Mo . With the NEMO-3 detector, a similar level of sensitivity can be reached for some other nuclei as well (with 10 kg of ^{82}Se , for example). It is precisely these two experiments (NEMO-3 and CUORICINO) that will carry out the investigations of double beta decay over the next three to five years. The Next-generation experiments, where the mass of the isotopes being studied will be as grand as 100 to 1000 kg , will have started within five to ten years. In all probability, they will make it possible to reach the sensitivity to the neutrino mass at a level of 0.1 to 0.01 eV .

Acknowledgments

I would like to thank Prof. C.S. Sutton for his useful remarks. A portion of this work was supported by grants from INTAS (03051- 3431) and NATO (PST CLG 980022).

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